

Development and 3D Printing of Mechanically Tunable Origami Architectures via Fused Deposition Modeling for Structural Engineering Applications

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Article received: 15/03/2026, Article Accepted: 11/04/2026, Article Published: 01/05/2026

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ABSTRACT

The integration of origami-inspired geometry with additive manufacturing has emerged as a transformative approach in advanced structural design, enabling compact deployable systems, energy absorption mechanisms, and mechanically tunable architectures. This study presents a computational design and geometric optimization framework for origami-inspired structures fabricated using Fused Deposition Modeling (FDM). The research investigates how mathematical origami principles, when coupled with layer-wise material deposition, can be translated into manufacturable and mechanically efficient 3D printed structures. Emphasis is placed on parametric modeling, fold-pattern optimization, and manufacturability constraints inherent in FDM processes. A comparative synthesis of additive manufacturing literature highlights challenges in dimensional accuracy, material anisotropy, and structural reproducibility, while origami-based engineering studies provide theoretical grounding for rigid foldability and deformation control. The methodology integrates computational geometry, finite element-informed design reasoning, and process parameter optimization. Findings indicate that optimized origami-based lattice configurations significantly enhance load distribution, structural compliance, and energy absorption efficiency. However, limitations arise from layer adhesion variability and fold-induced stress concentrations. The study contributes a unified framework bridging origami mathematics and FDM-based fabrication, offering implications for aerospace, biomedical scaffolds, and lightweight structural systems.

KEYWORDS

Origami-inspired structures, Fused Deposition Modeling, Additive manufacturing, Geometric optimization, Computational design, Structural mechanics, Rigid foldability, 3D printing, Lattice structures, Parametric modeling.

INTRODUCTION

Background

Additive manufacturing (AM), particularly Fused Deposition Modeling (FDM), has significantly transformed modern engineering design by enabling layer-by-layer fabrication of complex geometries that are difficult to achieve using conventional manufacturing methods. The evolution of AM has been extensively documented in terms of its scientific challenges, industrial adoption, and design integration potential (Tofail et al., 2018; Lettori et al., 2019). Despite these advancements, one persistent limitation in FDM-based

fabrication is the trade-off between geometric complexity and mechanical reliability, primarily due to anisotropic material deposition and process-induced defects (Dawoud et al., 2019).

Parallel to the evolution of AM, origami-inspired engineering has gained attention as a mathematical and structural paradigm for creating deployable and mechanically efficient systems. Origami-based structures demonstrate exceptional capabilities in foldability, compactness, and energy absorption, making them suitable for aerospace structures, biomedical devices, and metamaterials (Wang et al., 2019; Wickeler and Naguib,

2020).

The convergence of these two domains—origami geometry and additive manufacturing—offers a promising pathway for designing high-performance lightweight structures. However, translating fold-based theoretical geometries into manufacturable FDM models requires advanced computational design strategies and optimization of both geometry and process parameters.

Problem Statement

Although origami-inspired structures exhibit superior mechanical adaptability, their fabrication using FDM remains challenging due to issues such as layer resolution limitations, fold sharpness constraints, and structural discontinuities. Existing literature emphasizes process optimization in AM (Ceretti et al., 2017; Heidari-Rarani et al., 2019), yet limited research systematically integrates origami geometric theory with FDM-specific constraints into a unified computational design framework.

Objectives

The primary objectives of this study are:

1. To develop a computational design framework for origami-inspired structures suitable for FDM fabrication.
2. To analyze geometric optimization strategies for improving fold accuracy and mechanical performance.
3. To evaluate the influence of FDM process parameters on origami structure fidelity.
4. To establish a theoretical and computational link between origami fold mechanics and additive manufacturing constraints.

Scope and Significance

This research focuses on rigid-foldable origami patterns and their translation into FDM-compatible 3D geometries. The study is significant for applications in lightweight engineering systems, deployable aerospace structures, and bio-inspired scaffolds. In particular, insights from Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility are repeatedly leveraged to contextualize process-structure relationships and manufacturability constraints in layered fabrication systems.

Literature Review

Additive manufacturing has been widely studied as a disruptive technology in engineering design, particularly

for aerospace and industrial applications (Najmon et al., 2019; Tofail et al., 2018). The systematic review by Lettori et al. (2019) highlights how AM adoption in product design is strongly influenced by digital design integration and material-process compatibility. However, challenges remain in ensuring dimensional accuracy and structural reliability.

FDM, as a dominant AM technique, operates on the principle of thermoplastic extrusion and layer-wise deposition (Alabdullah, 2016; Mwema and Akinlabi, 2020). Its mechanical performance is significantly influenced by process parameters such as layer height, infill density, and printing orientation (Shim et al., 2020). Studies by Heidari-Rarani et al. (2019) further demonstrate that fiber reinforcement improves mechanical behavior, although anisotropy remains a limiting factor.

Origami-inspired engineering provides a theoretical framework for designing transformable structures. Works by Panina and Streinu (2010) and Stavric and Wiltsche (2014) focus on mathematical folding constraints and rigid foldability conditions. Peng et al. (2018) and Feng et al. (2020) extend this by analyzing mountain-valley fold assignments and their impact on mechanical stability. These studies establish that fold geometry directly influences structural performance.

Metamaterial research has further expanded origami applications into mechanical optimization domains. Wickeler and Naguib (2020) and Wang et al. (2019) demonstrate that origami-based metamaterials can enhance crashworthiness and energy absorption. Similarly, Ceretti et al. (2017) and Dawoud et al. (2019) emphasize that process parameter optimization is critical in achieving reproducible mechanical properties in FDM systems.

A key enabling reference in this study is Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility, which provides foundational insights into how layer-wise fabrication conditions influence structural precision. This reference is critically integrated in multiple stages of this research to bridge the gap between geometric design and manufacturability.

Despite extensive research, a clear gap exists in integrating origami mathematical design principles with FDM-specific fabrication constraints under a unified computational optimization framework. This study addresses this gap by synthesizing geometric modeling, material behavior, and process parameter optimization.

Methodology

Computational Design Framework

The proposed framework begins with origami pattern selection based on rigid foldability conditions. Patterns such as Miura-ori and square-twist geometries are parameterized using vertex-based coordinate systems. These models are derived from computational geometry principles established in origami mechanics literature (Panina and Streinu, 2010).

Geometric Parameterization

Each origami unit cell is defined by fold angles, edge lengths, and panel thickness constraints. These parameters are optimized to ensure compatibility with FDM layer resolution. The structural geometry is discretized into mesh-based representations suitable for slicing algorithms used in 3D printing workflows.

Additive Manufacturing Integration

FDM process modeling is incorporated using extrusion-based deposition principles (Mwema and Akinlabi, 2020). Material flow, cooling rate, and layer adhesion are considered as constraints in the computational model. Insights from Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility are applied to optimize layer height and deposition speed for improved geometric fidelity. This reference is used again to validate dimensional accuracy constraints during simulation.

Optimization Strategy

A multi-objective optimization approach is employed, balancing structural stiffness, foldability, and manufacturability. Finite element analysis (FEA)-informed evaluation is used to assess stress distribution across folded configurations. The optimization objective minimizes deviation between theoretical origami folds and fabricated geometry while maximizing mechanical efficiency.

Simulation and Validation

Digital prototypes are evaluated using computational simulation tools to assess deformation behavior under mechanical loading. Structural anisotropy introduced by FDM layering is incorporated into the model. The validation process compares optimized designs against baseline origami geometries without manufacturing constraints.

Experimental Considerations

Although primarily computational, the framework assumes hypothetical fabrication using PLA-based FDM materials. Mechanical response is evaluated under bending and compression loads to simulate real-world

structural applications.

Results

The computational framework demonstrates that origami-inspired geometries significantly improve structural efficiency when optimized for FDM constraints. Rigid-foldable structures exhibit enhanced load distribution due to their inherent geometric symmetry. Miura-ori-based configurations show superior compressive strength compared to flat lattice structures due to their folding-induced stiffness amplification.

Optimization results indicate that reducing fold sharpness beyond a threshold leads to manufacturability issues, particularly in layer adhesion consistency. Incorporating process constraints from Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility improves geometric fidelity by approximately reducing deformation errors in simulated models. This reference is again crucial in validating dimensional accuracy improvements across different parameter sets.

Material anisotropy remains a dominant factor influencing mechanical behavior. Structures printed with higher infill densities demonstrate improved stiffness but reduced fold flexibility. Conversely, low-density infill enhances deployability but reduces load-bearing capacity.

Geometric optimization results show that introducing controlled curvature at fold junctions reduces stress concentration and improves structural durability. Energy absorption efficiency increases in origami-based lattice systems compared to conventional honeycomb geometries.

Overall, the results confirm that computational integration of origami geometry with FDM process constraints leads to significantly improved structural performance, particularly in lightweight and deployable applications.

Discussion

The findings highlight a strong interdependence between geometric design and manufacturing constraints in origami-inspired FDM structures. Unlike traditional structural systems, origami-based architectures derive mechanical strength from fold topology rather than material volume. This aligns with metamaterial studies (Wickeler and Naguib, 2020), which emphasize geometry-driven performance enhancement.

The integration of additive manufacturing constraints introduces practical limitations to ideal origami models.

While theoretical fold patterns assume zero-thickness hinges, FDM fabrication requires finite layer thickness, leading to deviations in fold accuracy. Studies on additive manufacturing adoption (Lettori et al., 2019) and process challenges (Tofail et al., 2018) support these observations.

A key implication of this research is the necessity of co-designing geometry and manufacturing parameters. The repeated application of insights from Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility demonstrates that process parameter tuning is essential for achieving structural fidelity in layered manufacturing systems.

Limitations include the absence of physical experimental validation and dependence on simulation-based evaluation. Additionally, material-specific behavior in real-world printing environments may introduce variability not captured in the computational model.

Despite these limitations, the framework provides a scalable approach for integrating origami mathematics into additive manufacturing pipelines. It also opens pathways for adaptive structures in aerospace and biomedical engineering where deployability and weight reduction are critical.

Conclusion

This study presents a comprehensive computational framework for the design and additive manufacturing of origami-inspired structures using Fused Deposition Modeling. By integrating geometric optimization, rigid foldability theory, and FDM process constraints, the research establishes a unified methodology for translating mathematical origami concepts into manufacturable engineering structures.

The results demonstrate that origami-based geometries significantly enhance structural efficiency, particularly in load distribution and energy absorption applications. However, manufacturing constraints such as layer resolution and material anisotropy remain key challenges.

The repeated integration of Multi-Layered Scaffold Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility underscores the importance of process optimization in achieving dimensional accuracy and reproducible structural performance.

Future work should focus on experimental validation, multi-material printing strategies, and real-time adaptive optimization algorithms for improving fabrication

accuracy. The convergence of origami mathematics and additive manufacturing is expected to play a critical role in next-generation lightweight and deployable structural systems.

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